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A MEASUREMENT OF THE INTENSITY AND POLARIZATION OF MUONS PRODUCED DIRECTLY BY THE INTERACTIONS OF PROTONS WITH NUCLEI

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Abstract

We propose to investigate the intensity and polarization of high energy muons produced very near the point of interaction of protons with heavy nuclei. Such measurements would be sensitive to the production of W's, the intermediate weak interaction vector boson, and to the production of muon pairs through a virtual photon. The measurements would also constitute a search for the X-process postulated by the Utah group from their cosmic ray measurements of muon flux. The polarization of muon fluxes which correspond to production cross sections of the order of 10^{-34} $cm^2/sr \cdot GeV/c$ can be measured while the intensity of directly produced muon fluxes can be measured corresponding to cross sections of the magnitude of $10^{-36} cm^2/sr \cdot GeV/c$. These differential cross sections correspond to total cross sections of the order of $10^{-35} cm^2$ and $10^{-37} cm^2$ respectively.

The external beam in area I would be directed upon a uranium target of varying density set adjacent to the steel neutrino shielding. Measurements of the polarization and the intensity of muons which pass through a large fraction of the shielding will be made as a function of the effective

target density. The results of these measurements, extrapolated to infinite target density, constitute a measurement of the flux and polarization of those muons produced directly by nucleon-nucleon interactions or as the result of the decay of weakly interacting particles ~~is~~ so produced.

Physics Justification

We are interested in measuring the intensity, charge, and polarization of muons produced very near the point of interaction of high energy protons with nucleons. Such measurements may illuminate several problems of interest:

1. Such measurements constitute a search for the W, the vector boson considered to mediate the weak interactions. These searches may extend to larger W masses than searches using neutrinos.
2. The measurements would provide a measure of the production of muon pairs through the electromagnetic interactions and then provide information on the time-like electromagnetic form factors of the nucleon where the excited nucleon states are also involved. Such measurements would be related to the space-like electromagnetic form factors relevant to the inelastic scattering of electrons from nucleus.
3. The measurements would detect any substantial X-process of muon production where the X-process is the name given by the Utah group to the anamalous production mechanism suggested by their measurements of cosmic ray muon flux at very high energies.
4. There is also the possibility of other esoteric results: any appreciable production of heavy leptons would be detected.

We shall address ourselves, in detail, to these various problems in order.

W-Production

A question central to our understanding of weak interactions at this time is the problem of the existence of the intermediate vector boson.

If the boson exists, important properties of the boson, such as its spin and coupling to fermions, are already known through analysis of the well known properties of weak interactions. In particular, for any postulated mass, the production cross section for the boson - called here, conventionally, the W - can be calculated fairly reliably for production processes which essentially involve only the weak interactions. The results of such calculations concerning the production of W-bosons by the interaction of high energy neutrinos with matter together with the relevant experiments has excluded the possibility that the W exists with a mass[1] much less than 2 GeV/c^2. Limitations on the available flux of high energy neutrinos from the available accelerators makes it difficult to extend this limit to higher values of masses using this method. There are kinematic advantages which suggest that experiments designed to observe the production of the W in the interaction of hadrons, produced by existing accelerators such as the AGS, might have been successful in producing observable numbers of W-bosons even if their mass was as large as 5 GeV/c^2. Although no W-particles were observed in the experiments which have been conducted, these experiments[2,3] were not sufficiently sensitive to detect W's with large mass. We address ourselves to the limitations of these measurements -- especially our previous measurement[3] at the AGS -- later.

Experiments designed to detect the interaction of high energy neutrinos deep underground[4] have been compared to the results of measurements of neutrino interactions at accelerators to suggest[5] that the W-mass is not smaller than 5 GeV/c^2. It is difficult to reconcile the measured interaction rate underground with the enhanced interaction rate one might expect if the channel producing W's was open for small W masses.

But, there are aesthetic reasons for believing that a boson exists and that the mass of the boson is not enormously large. Since other interactions, such as the electromagnetic interaction, the strong interactions, and even the gravitational interaction, can be described as a vertex of three lines of a Feynman type diagram, it is attractive to believe that the weak interactions can be described in this way also. Of course, if the boson is very heavy, perhaps infinitely heavy, the concept of the boson loses operational significance. However, a heavy boson requires a large coupling constant in order to satisfy the observations on the weak interaction decays at low energy.

The coupling constant is:

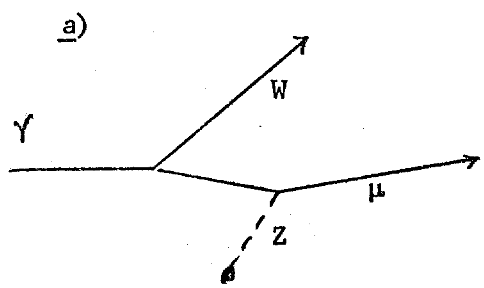
$$\frac{g_W^{\ 2}}{\hbar c} = \frac{10^{-5} M_W^{\ 2}}{\sqrt{2}\ M^2} \quad \text{where} \quad \frac{e^2}{\hbar c} = 1/137$$

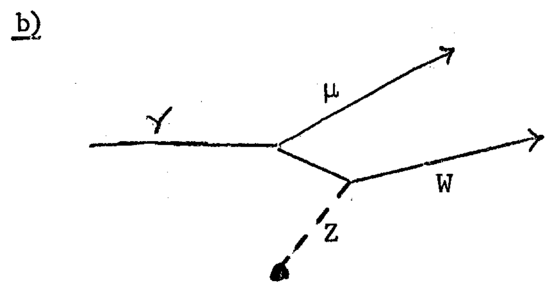
where M is the nucleon mass. The coupling constant is small only if M_W, the W mass, is not extremely large. If the W mass is very large, e.g., 30 BeV/c^2, the coupling constant will be of the same magnitude as the electromagnetic coupling constant. In this case, the weakness of the weak interaction, as it applies to observed decays, results from the fact that the energy of the decays is small compared to the W mass. However, the K_2° - K_1° mass difference results from virtual states coupled through the weak interactions and there is no important limit to the energy of the virtual states involved; if the coupling constant is actually very large it would appear that these very energetic states should contribute to the mass difference in an important way and it is then difficult to understand why the mass difference is as small as it is[6]. From this point of view, it is difficult to believe that the boson mass is very much larger than 10 BeV/c^2.

In view of the importance of the question of the existence of the intermediate boson it has seemed essential to us that further investigations be made and it is plausible that searches using hadron interactions, in particular interactions of the proton beam from the NAL accelerator, may be best suited to find the W. Accelerators produce much larger fluxes of strongly interacting particles than neutrinos, the maximum energy of the strongly interacting particles is appreciably greater than the effective energy of the neutrino fluxes, and dimensional considerations suggest that the cross sections for W production by hadrons could be appreciably larger than cross sections for the production by neutrinos.

Figures 1a and 1b represent Feynman diagrams which illustrate the important processes for the production of W-bosons by neutrinos.

Figure 1





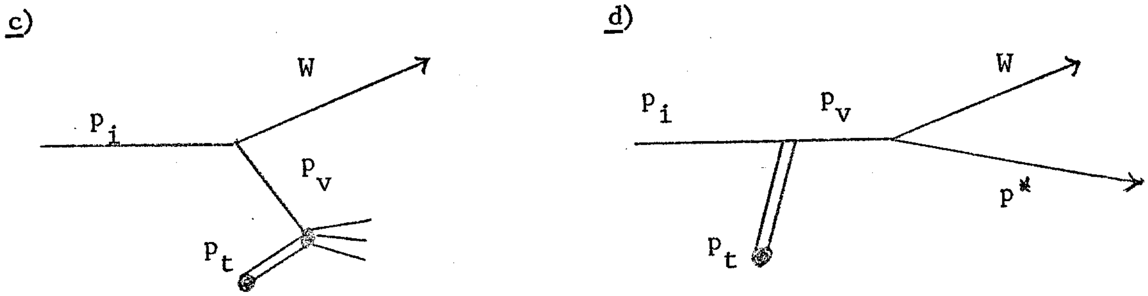
A neutrino disassociates virtually into a W and a muon. In diagram a), the virtual μ is scattered by the coulomb field of a nucleus Z. In diagram b), the W is scattered by the nuclear coulomb field. The nominal strength of the reaction is:

$$I \approx g_W^{2} \cdot e^{2} \cdot e^{2} \cdot F(t)^{2} \qquad (1)$$

where g_W^{2}, is proportional to the probability of the weak interaction transition at the (ν, W, μ) vertix, e^2 is proportional to the probability of the lepton or W absorbing a photon, and $e^{2} \cdot F(t)^{2}$ is the probability of a proton in the nucleus emitting a virtual photon with a four momentum equal to t: F(t) is an electromagnetic form factor for the emission of a virtual photon by the proton. If the value of t is small, i.e., $t^{-\frac{1}{2}} < a$, where a is the nuclear radius, the whole nucleus will act coherently. At the four-momentum transfers considered here, the nuclear coherent production can usually be neglected. Since all of these factors are well defined and small, the cross sections for the processes of Figs. 1a and 1b can be calculated accurately and reliably. An interpolation and extrapolation of existing calculations[7] suggests that the cross section for the production of 10 GeV/c^2 W-bosons by 200 GeV neutrinos on protons will be about equal to $2 \cdot 10^{-37} cm^2$ and for 500 GeV protons the cross section will be about $5 \cdot 10^{-37} cm^2$.

There is considerably experimental evidence that strong interaction processes are most important when no large four-momentum transfers occur. Qualitatively, reduction of the probability of high momentum transfer reactions can be understood as a consequence of different, but related, phenomenological descriptions of the interaction process: There is absorption in entrance and exit channels; the hadron mantles are weakly coupled to the hadron cores so the hadrons are easily broken up at large momentum transfers; and the radiation damping & radiation resistance to large momentum transfers of hadrons is very great since the strong interaction coupling constant is very large. As a result of these various considerations it appears to us that production mechanisms which involve small momentum transfers are likely to dominate the production of W-bosons by the interactions of hadrons. In particular, we believe that the processes suggested by the Feynman diagrams are likely to be particularly important.

Figure 2



In these diagrams, p_i represents the incident nucleon, p_v the intermediate or virtual nucleon, p_t the target nucleon, and p_f the final state nucleon.

The character of the reactions which are represented by these diagrams can be understood to some extent in terms of simple qualitative models. The incident nucleon, which will be a proton, can be considered to be in a virtual state of a neutron and a W^+ part of the time. Since the weak interaction current is partially conserved, the W charge of the baryon complex is well defined independent of the virtual state spectrum of the proton. If the fast clothed proton in a virtual state of a W plus a bare nucleon, or a W plus other nucleon states, passes through matter, the strongly interacting hadrons will be absorbed while the weakly interacting W will pass through. It is this kind of interaction which is suggested by the diagram of Fig. 2c. The virtual particle p_v represents the baryon states which are absorbed.

It is also possible that the incident nucleon is disturbed by the interaction with the target nucleon so that the virtual states of the W plus nucleon or W plus baryon states are pushed into the mass shell by the small momentum transfer which occurs in the collision. The collision may typically involve the exchange of a meson or even the diffraction scattering of the nucleon or exchange of a Pomeronchon. This kind of scattering disassociation is represented by the diagram 2d.

The process which is represented by diagram 2c, is analogous to the process of diagram 1a, for the production of W's by neutrinos. The weak interaction vertex of diagram 1a is replaced by the weak interaction vertex (p, W, p); the transfer of the photon from the nucleus to the muon is replaced by the strong interaction between the two nucleons. Since the strong interaction is much stronger than the electromagnetic interaction, and the two weak interaction probabilities are nominally equal, it would appear that the cross section for the production of W's by hadron interactions might be very much larger than the cross section for the production by neutrinos. The interaction intensity factors, comparable to the factors of equation 1, are:

$$I \approx g_W{}^2 \cdot G^2 \cdot G^2 \cdot F_s(t') \cdot F_W(t)^2 \qquad (2)$$

where $g_W{}^2$ is again the square of the weak interaction coupling constant which is proportional to the probability for the transition (n, W, n) at small momentum transfer, G^2 is the square of the strong interaction coupling constant which occurs twice for the interaction of the target nucleon with the virtual nucleon.

Unlike the neutrino, the nucleon is an extended structure. While the weak interaction coupling for the vertex (n, W, n) is equal to the coupling for the vertex (ν, W, μ) for the small momentum transfers (aside from unimportant SU_3 Clebsch-Gordan coefficients and Cabbibo factors), at large momentum transfers the effective coupling will be reduced in a manner expressible by form factors which are probably nearly identical to the electromagnetic form factor. From the CVC description of the weak interactions, we have strong reasons to believe that the weak interaction nucleon vector form factor is the same as the nucleon isovector electromagnetic form factor and the nucleon axial vector form factor is likely to have a somewhat similar form. Then we write $F_W(t)$ as a representative form factor for the weak interaction vertex where $t = -M_W{}^2$ is the four momentum transfer at that vertex to the virtual particle which is here a baryon state.

Unitarity restricts the importance of the G^4 factor in such a way that the cross section for nucleon-nucleon interactions on the mass shell (for real nucleons) is nearly independent of energy. There is considerable evidence that the interaction of the two nucleons is such that large four-momentum transfers do not occur very often. This suggests that the nucleon-nucleon total cross section becomes very small for the interaction of nucleons such that, $t > M_n{}^2$. In the notation of equation 2, that effect is summarized by the form factor $F_s(t')$ where t' is the four-momentum transfer in the nucleon-nucleon interaction.

In the absence of all form factor effects - that is, all form factors are set equal to 1.0 - the ratio of the cross sections for W production by nucleons on nucleons and by neutrinos on nucleons might be expected to be of the order of $G^4/e^4 \approx 10^5$. While it would appear that the effect of the various form factors would be such as to reduce this ratio, it is hardly transparently obvious as to the extent of the reduction, if any. We have attempted to make estimates of the cross sections for the production of W's by the interaction of 200 and 500 GeV protons with nucleons and to further determine the qualitative and quantitative effects of various form factor choices.

For high energy W production in the forward direction, we might expect that the production would be dominated by processes of the form suggested by the diagrams of Fig. 2c and 2d. The mechanism of 2c is essentially a baryon exchange mechanism while the process shown as 2d is a kind of dissassociation mechanism. If the exchanged particle is considered to carry the quantum numbers of the vacuum -- that is a Pomeranchuk pole, this will be a diffraction dissassociation. Both processes should produce high energy W particles which will decay with some branching ratio[7] which may be near 25%, to a muon and a neutrino and the muons which are emitted in the forward direction in the center of mass system will have a very large energy in the laboratory system.

It is interesting to estimate the cross sections for the production of W-bosons from these processes. The construction of the estimates illuminates the uncertainties in our understanding of the processes which are involved and the final results, which are largely determined by kinematic considerations rather than the details of calculations, provide us with models for the construction of experiments.

We can calculate the cross section for the production of W's with a mass M_W, through the mechanism defined by the diagram 2c using the prescription of Chew and Low[8], as a function of the square of the invariant mass of the virtual baryon, Δ^2, and the square of the invariant mass, ω^2, of the system of the virtual nucleon and the target nucleon. The cross section is then,

$$\frac{d^2\sigma}{d(\Delta^2)\,d(\omega^2)} = \frac{\mu^2}{2\pi} \cdot \frac{M_W}{Mp} \; \frac{\frac{1}{4}\,\omega^4 - \omega^2 Mp^2)^{\frac{1}{2}}}{Q^2} \; \frac{\sigma(\omega)}{(\Delta^2 - Mp^2)^2} \qquad (3)$$

where σ is the nucleon-nucleon cross section at an energy ω, Q is the momentum of the incident proton and U is the matrix element for the weak interaction vertex, taken here as:

$$4\pi U^2 = \frac{G^4}{4Mp^2} \; \left| (p_i + p_v) \cdot (p_\mu - p_\nu) \right|^2 \int \frac{dq^2}{\left| (M_W - i^{\Gamma/2})^2 + q^2 \right|^2} \qquad (4)$$

where p_i, p_v, p_μ, and p_ν are the four-momenta of the incident proton, the virtual nucleon, the muon form the W decay and the neutrino. The W decay width is equal[9] to $G^2 M_W^{\ 2}/6\pi$ B, where B is taken here[10] as $\frac{1}{4}$, and G^2 is the weak interaction coupling constant given by $G^2 M_p^{\ 2} = 10^{-5} M_W^{\ 2}/\sqrt{2}$.

The expression of Equation 3 should be modified by the product of two form factors. From the CVC hypothesis we might expect that the form factor for the weak interaction vertex (p, W, n) can be taken as nearly the same as the time-like isovector electromagnetic form factor for the nucleon at a momentum transfer $q^2 = M_W^{\ 2}$. As we will point out later, this assumption may be much too restrictive. A second form factor, exp(-3t), is also used where t is the absolute square of the minimum four-momentum transfer required to put the virtual baryon on the mass shell. This factor does not affect the cross sections very much.

The matrix element of Equation 4 represents an approximation where the spins of the baryons are suppressed by considering the baryons as scalar particles. In this approximation there is but one amplitude and one form factor which can be considered as an appropriate average over the several form factors required for a more complete description (which does not seem to be warranted at this time).

Aside from this neglect of spin effects, the formula of Equation 3 represents an approximation which neglects all singularities in the amplitude as a function of the variable Δ^2 except the nucleon pole. Therefore, the expression is not likely to be useful except where $(\Delta^2 - M_p^{\ 2})^2$ is quite small.

This is not the case for the results presented here where Δ^2 is typically of the order of $-M_p^{\,2}$. We can estimate the effect of the extrapolation by borrowing from the results of other baryon exchange measurements and multiplying the expression for the differential cross section by a factor exp $[B(s) \cdot (\Delta^2 - M_p^{\,2})]$ where s is the square of the center-of-mass energy and $t = -\Delta^2$ is the square of the four-momentum transfer. If we take, $B = 0.9$ ln s, we have a Regge form[11] for the factor and both the variation of cross section with t and s and the magnitudes of the cross sections calculated in this way are consistent with cross sections measured for similar baryon exchange reactions.[12] While this approximation should be good for reactions where we can identify the intermediate state as a nucleon - or a nucleon Regge pole - the experimental observations also include productions when other intermediate baryon states are involved. This is very important when we consider electromagnetic form factors and we will return to this point later.

The results of specific calculations, made using these recipes, of the production of muons through W-decay, where the W-bosons are produced by the interaction of 200 GeV and 500 GeV protons with nucleon targets, are presented in Table 1. Here the branching ratio for the decay of the W to a muon is taken as 25%. In these calculations of the production of W-bosons through the vector part of the weak interaction contribution to the (n, W, n) vertex, we assumed, for the purpose of explicitness, that the time-like isovector form factor was equal to one. The cross sections should then be multiplied by the appropriate form factor at $t = -M_W^{\,2}$. It must be emphasized, in any case, that the results given in Table 1, modified by the inclusion of the form factor, represent at best only a part, and perhaps but a very small part, of the total W-production.

If we knew and understood the whole structure of baryons, we could carry out a calculation such as that of Equation 3, for all possible intermediate baryons and add the results. Each of these production mechanisms would be effected by the inclusion of the time-like form factor for W production at the W vertex. From what we know of the analogous (or almost equivalent) electromagnetic form factor, it seems likely that the individual form factors would be small. In some sense, each of the baryon states is fragile, or at least, an extended object. However, the recent measurements on the inelastic scattering of electrons from nucleons shows that for the sum of all possible excited baryon states, (which in this problem, is all possible intermediate states) the form factors are large and do not fall off very much with increasing momentum transfer. The nucleon acts as if it were made up of a cloud of point-like partons (or quarks?). We then have reason to believe that the estimate of our effective form factor in Equation 3, may be a reasonable approximation to including all possible intermediate states.

We believe that the diffraction dissassociation mechanism is likely to be much more important than the baryon exchange mechanism at high energies. For other reactions, we note that those reactions which can procede through the exchange of a Pomaranchuk pole have cross sections which do not decrease with energy, and are therefore large at high energies, while reactions described by the exchange of a massive particle decrease rapidly with energy and are then very small at high energies. Moreover, an explicit estimate of the cross section for the production of W-bosons through this kind of process suggests that the cross section may indeed be quite large and very much larger than the cross section for the exchange mechanisms.

We make an estimate by assuming that the diffraction dissassociation mechanism dominates the total cross section at the energies of interest and that the ratio of W production to pion production is about proportional to the relative probability of finding a W and a pion in the field of the nucleon. Then

$$\sigma_W/\sigma_\pi = (g^2/G^2)\cdot(a_W/a_\pi)^3 \quad \text{where} \quad a_W = h/M_W c \text{ and } \quad a = h/m_\pi c.$$

We take the pion-nucleon coupling constant as $G^2 = 1$ and

$$g^2 = 10^{-5}(M_W/M_p)^2/\sqrt{2}.$$

Then if we associate σ_π with the total cross section of about $3\cdot10^{-26}\text{cm}^2$,

$$\sigma_W = 3\cdot10^{-26}\cdot10^{-5}(M_\pi{}^3/M_W M_p{}^2)/\sqrt{2} = 6\cdot10^{-35}\text{cm}^2 \quad \text{for} \quad M_W = 10 \text{ GeV}/c^2$$

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One might argue that the effective coupling to the W on the mass shell will be grossly overestimated as g^2 is defined for zero mass bosons. Or, in other words, the result should be modified by a form factor which would be essentially the time-like nucleon form factor at $t = -M_W^2$. However, again, the parton model, suggested by the inelastic electron scattering data, would give a large effective form factor if we consider those transitions which leave the nucleon in an excited state. Since the experiments which we are considering here, detects the W produced together with any hadron state which is not too massive, there is an effective integration over (almost) all final baryon states and we believe that the effective form factor will then be near one and insensitive to the W mass.

Of course this mechanism is expected to be important only if the four-momentum transfer is not important. This can be stated more quantitatively by remarking that the cross section can be expected to vary somewhat as exp (3t) where t, the square of the four-momentum transfer is $(GeV/c)^2$ is expressed as $t = -(M^{*4}/4P^2)$ where $M^* = M_W + M_b$ and P is the momentum of the incident nucleon and M_b is the invariant mass of the residual hadron state. If M_b is not much greater than $2\,M_p$, then the cross section should remain large up to masses of 10 GeV/c^2 for P = 200 GeV/c, and 16 GeV/c^2 for P = 500 GeV/c.

Though the production of high energy muons through the production and decay of high energy W-particles may be as small as 10^{-6} times as important as the production through the decay of high energy mesons, the mesons have a comparatively long lifetime compared to the W and the mesons can be largely removed before they decay by absorbing them in heavy material, such as uranium. If the mesons are absorbed in this way, it seems probable that the flux of very high energy muons produced at small angles by the interaction of 200 GeV protons or 500 GeV protons with a very thick target of heavy material may result largely from the production and decay of the W - the intermediate vector boson - if the mass of the W is between 5.0 and 15.0 GeV/c^2.

We estimate that the negative particle flux corresponds to a cross section

$$d\sigma/dE\cdot d\Omega \approx 10^{-26}\,cm^2/ster\cdot GeV$$

where the flux is dominated by the production of pions and K-mesons. The probability of a pion decaying to a muon before interacting with the uranium of the target will be about 10^{-5} and, at this high energy, the muon flux will be less than the pion flux by about a factor of 10, even as the mean muon energy is considerably smaller than the mean pion energy. Therefore, we expect about as many muons from W-production as background from pions when both fluxes are examined in the forward direction.

Further discrimination can be made by moving to small angles from the forward direction. At an angle such that the transverse momentum of the muon is about 2.0 GeV/c, the flux of muons from pions or K-mesons will be reduced by a factor of the order of $\exp(-5) = 7 \cdot 10^{-3}$, while the muon flux from the decay of massive W's will scarcely be reduced from the flux in the forward direction.

The graphs of Figs. 3 and 4 show the locus of the maximum muon intensities from the decay of W-bosons as a function of muon energy and angle. The cross sections are derived from the calculations of Equation 3. Since the loci of the maxima result primarily from kinematic restraints, muons produced from the decay of Ws produced through diffractive mechanisms will be produced at similar angles and energies. Estimates of the flux of muons from pion decays are also shown on the graphs.

The muons which result from the decay of an intermediate boson can be differentiated from the remaining muons produced through the decay of mesons in two ways: 1) The density of the absorber can be varied - the intensity of muons from meson decay will be nearly inversely proportional to the density of the absorber in as much as the absorption of the mesons will be reduced. And, 2) the Muon polarization can be measured - muons from the decay of the vector boson will be polarized in the opposite direction than those which result from the decay of pseudoscalar mesons. In either case, the highest energy muons will result from decays such that the muons are emitted in the forward direction in the rest frame of the parent particles and neutrinos are emitted traveling backwards. For decay of positive parent particles the neutrinos will be emitted with their spin vectors anti-parallel to their direction of motion. Then for the decay of spin one particles, in the limit $M_\mu/M_\omega \to 0$, the positive muon will have its spin parallel to its direction of motion while the muons which result from the decay of the spin zero mesons will have their spin directed anti-parallel to the direction of motion. This will also obtain in the laboratory system for the highest energy muons so a measurement of the polarization of the muons will provide important information concerning their origin.

More generally, longitudinal polarization of muons from W-decay is,

$$P = 1 - (2M_{\mu}^{2}/M_{W}^{2}) \cdot (E_{W}/E_{\mu})$$

for positive muons. For muon energies near the maximum total energy and then near the maximum possible W energy, the polarization will be very near 100%.

Electromagnetic Production of Muon Pairs and the Time-Like Electromagnetic Form Factors

Yamaguchi[9] has suggested that the muons produced promptly by the electromagnetic interactions will dominate the prompt muon spectrum and obscure any production of muons through the decay of a real intermediate boson. Inversely, the study of the prompt muons from electromagnetic form factors of the nucleon which are of interest in themselves and then add to the information concerning the existence of the W. Yamaguchi calculates the ratio production of muons from W's to muons produced electromagnetically: From Equation 5 of his paper,

$$ds_{w}/ds_{e} \leq (M_{w}/10\ M) \cdot (M_{w}^{2}/dq^{2})$$

where ds_{w} represents the cross section for the production of a W of a definite momentum, produced at a definite angle, which subsequently decays into a muon; ds_{e} represents the cross section for the production of a virtual photon at the same angle and with the same momentum which also decays into muons; the invariant mass of the photon is in the range, dq. Here M_{w} is the mass of the W, and M is the mass of the nucleon. The basis of the calculation is the assumption that the electromagnetic form factor and the weak interaction form factors are very nearly identical. While the success of the conserved vector current description of weak interactions makes it seem very likely that the weak interaction vector form factor is the same as the electromagnetic vector form factor, it is hardly obvious that the acial vector weak interaction form factor is similar to the vector form factor.

While Yamaguchi's arguments that the electromagnetic production of muons is likely to mask any production through W-decays, is not necessarily valid for all experiments, his suggestion shows that one might obtain information concerning W-production and electromagnetic processes by observing this electromagnetic production of muon pairs.

Transitions through virtual photons should produce equal numbers of the negative and positive muons in any interval of momentum or angle while any high energy flux of pions or W's will be primarily positive and give rise to positive muons upon decay. The difference between the positive and negative muon flux can then be measured and safely considered to be free from effect of the purely electromagnetically produced muons. Further, muons from electromagnetic processes will not be expected to exhibit any particular polarization.

In our proposed experiment, it appears that we will have an effective resolution at least as good as $dq = M$, where M is the mass of the nucleon. In that case, we expect a ratio of ds_W/ds_e which is near two, where ds_W is the flux of muons from W decays and ds_e is the flux from electromagnetically produced muon pairs. Since we will observe a mechanism which is expected to produce predominantly positive muons from the decay of W^+ from the virtual spectrum of the positive protons, and the muons from electromagnetic phenomena must be equally divided between positive and negative muons, we should gain very nearly another factor of two, and our over all ratio of muons from W-decay and muons from electromagnetic processes might be nearly as good as four to one. Further, any sample which represents the difference between the positive muon flux and the negative muon flux will be free of any contribuion from any electromagnetic processes. The existence of the electromagentic processes and the information which they carry concerning the form factors is very important in allowing an evaluation of the W search. If no large invariant mass electromagnetically produced muon pairs are observed, it is then likely that the experiment is not sensitive enough to have detected W's of that invariant mass. On the other hand, if such electromagnetically produced muons, from pairs with a large invariant mass, are observed to be produced profusely and no W signal is observed, it is very likely that a W of this mass does not exist. Since the time like structure of the axial vector electromagnetic form factor is certainly somewhat different, and perhaps much different, that the vector form factor which, through the CVC description of weak interactions, is the same as the electromagnetic form factor, the possibility cannot be excluded that the W production is far greater than the production of muon pairs. Certainly, this is likely to be the case if the W mass is near the mass of an axial vector meson.

We also discuss an electromagnetic background process here. Yamaguchi[9] is also concerned about the background which might result from the production of muon pairs from photons which are derived from the decay of neutral pions. Since fewer neutral pions will be produced at high energies than positive pions, we need only show that the muon production through the agency of neutral pion decays will be smaller than the muon contribution from the decay of charged pions. The absorption of the charged pion flux by the heavy material of the target results in a factor of about 10^{-5} reduction of the muon flux. The momentum spectrum of the decay muons is also less strongly peaked at high energy than the pion flux since some of the energy is taken off by the neutrino. The energy of the neutral pion is divided into the energies of the two muons. The muon spectra which results will be degraded from the pion spectrum much more than the muon spectrum from charged pions is degraded from the charged pion spectrum. The photon which is to produce the muon pair must do so in competition with the possibility of electron pair production. This ratio of muon pairs to electron pairs will not be larger than the factor, $(m/\mu)^2 = 2.5 \cdot 10^{-5}$ which is already smaller than the attenuation factor of 10^{-5} relevant to muons from charged pions. In summary, it seems quite unlikely that the muons from pair production by pi-zero gamma rays will be so large as one-tenth the contribution from charged pions. Further, as with all contributions from electromagnetic processes, any contamination of muons from W's from this source will be removed by subtracting the negative muon flux from the positive flux.

Muons from an X-Process

The Utah group[13] has investigated the intensity of high energy cosmic ray muons as a function of angle from the zenith. Conventional models of particle interactions suggest that these muons are largely daughters of meson produced in the primary interactions of the primary cosmic ray nucleon flux incident on the atmosphere. The primary spectrum varies steeply with energy - approximately as E^{-3} - and the secondary meson spectra is then expected to vary evenly more steeply with energy. It is then a good approximation to consider that any process which degrades the energy of a nucleon or meson effectively, removes that particle from the flux. The muons which are then observed are produced largely through the decays of mesons from primary showers where these mesons decay before interacting with the nucleons in the atmosphere. The mean free collision time is small compared with the decay time for the situations of interest in these measurements. Then a meson produced very high in the atmosphere, where the density is low, will decay more likely than a meson produced lower in the atmosphere.

It then follows, simply, that nucleons which enter the atmosphere at a large angle with the zenith and then interact high in the atmosphere, where the atmosphere is thin, create mesons in the forward direction which are more likely to decay to muons. It then follows, simply, that the flux of muons at a large angle with respect to the zenith should be much larger than the flux from the vertical. At very high energies, we can consider both the production and decay of mesons as colinear with the incident primary nucleon. A nucleon which enters the atmosphere at a large angle with the zenith will interact higher in the atmosphere than a nucleon which enters vertically and will then produce more mesons which decay into muons. In the limit that the mean time for collision is small with the decay time, and using the approximation that the curvature of the earth can be neglected, it is easy to show that the intensity of muons should vary as sec θ, where θ is the angle with the zenith. The results of the Utah group are not consistent with this simple predication and indicate that an appreciable flux of muons are produced in a manner which is independent of the density of the atmosphere. These directly produced muons constitute more than 50% of the flux observed by the Utah group and this anomalous muon flux is about 4% as great as the meson flux produced in the initial interactions. These comments apply to muons with energies of the order of 2500 GeV and we can presume that the energy of the primary nucleons is much higher than that - perhaps of the order of 10,000 GeV or more.

While it is possible that the process which provides the prompt muons - allied the X-process by the Utah group - has a definite threshhold at some very high energy, it is at least equally probable that there is a small cross section for the process at much lower energies. At 30 GeV, the ratio of the X-process to meson production was shown to be less than or equal to about one part of 10^6. An intensity, appreciably in excess at 200 GeV or 500 GeV should be easily detectable in our proposed experiment. Of course, we would then measure charge ratios and polarizations of the muons so produced.

Other Possible Muon Production Processes - Heavy Lepton Decays

It is certainly plausible that there are many lepton states in nature though we have observed only the two lowest states, electrons and muons. If heavier leptons exist, they must have masses in excess of the K-meson mass - or their decay to K-mesons would be observed ?? - but we have little other negative evidence. In general, such a lepton will be expected to decay into electron and muon states very rapidly. If the mass of the heavy lepton is much greater than the K-meson, the muons emitted from the decay of such a state will have polarizations which are largely "natural". That is, the positive muons will have a positive helicity while the negative muons emitted in the decays will be predominantly polarized with negative helicity. Since these helicities are, like the helicity of muons from W-decay, opposite to the helicity of muons from meson decay, prompt production of heavy leptons which decay into muons produces a specific signal in our experiment which differs from the expected background.

Although it seems unlikely that the production of such heavy mesons would be important, it is interesting to suggest a production mechanism which could produce a detectable signal. If the electromagnetic form factors in the time-like region for the sum of baryon states are not too small, we can expect some small production of large invariant mass lepton pairs. If the invariant mass is large compared to the mass of the leptons, the probability of production is independent of the lepton mass. Then, if there are very many heavy lepton states, the production of such lepton, which would then decay into muons and electrons, would be large. Though the heavy leptons would not themselves be produced in states of definite helicity, the muons produced as decay products will have a substantial polarization in both the center of mass system of the heavy lepton, and for those with large laboratory energies, the polarizations will be large in the laboratory system also.

Experimental Design and Arrangement

We propose to operate in the external beam designed to be used in the neutrino area where we would use shielding set up for the neutrino experiments. The diagram of Fig. 5 shows the character of the set up which we feel would be desirable if the primary proton energy were 500 GeV and if it seemed impractical to bury a magnet in the shielding.

The beam would be directed through a long evacuated beam pipe onto a target placed directly in front of the main neutrino shield. The target should be constructed of dense material, such as uranium or tungsten, in a manner such that the effective density can be varied. We now have a target of this type manufactured of uranium which was used for a similar experiment[3] at the Brookhaven AGS. Muons produced in the target then pass into the shielding immediately behind the target. It is desirable, though not essential, that a steel filled magnet be buried in the shielding where the field integral would be of the order of 100 kg·meters and the field extends over an area of the order of 100 cm^2. Those muons which pass through an appropriate length of shielding (about 700' of steel shielding if the beam energy is 500 GeV) would then pass through a final set of counters. Some of these muons will stop in a detector where the polarization and lifetimes of the stopped muons would be measured.

The counters would cover an area about 6' by 6' and would be used in conjunction with two other sets of counters placed upstream in the shielding and with the polarization detector. Both the final counters and the polarization detector would be placed so that their centers would lie about

6 feet from the beam line. This line corresponds to the center of intensity of particles with a transverse momentum of about 3.0 GeV/c. The actual transverse momentum of the particles accepted by these detectors would vary from this number as a result of the multiple scattering in the shield but this will be discussed in detail much later.

The polarization detector, which was constructed for our previous experiment at the AGS, is constructed of 23 sections, each consisting of a 4" aluminum slab 2' wide and 3' high and a scintillation counter the same size but ¼" thick. Muons which stop in the detector precess in a magnetic field applied perpendicular to the axis of the detector, which was aligned with the beam. The position of the muon stop along the axis of the detector is determined by those counters which indicate the passage of the muon, and the direction of emission of the positron from the muon decay and the time of this decay is determined by recording subsequent signals from these same counters. The component of polarization of the muon with respect to the beam direction is then determined through an analysis of the forward-back ratios of the electron decays from the precessing muons as a function of time. All of this information will be transferred to a small on-line computer which performs appropriate analyses of the data.

We propose to provide the target, the detector, and the computer together with the appropriate interface electronics. All of these components exist and have been tested in our previous experiment[3] at the AGS. The target was subjected to a beam energy of only about 2 kilowatts at the AGS. It seems that it will be easy to supply cooling so that energies of the order of 20 kilowatts can be absorbed in the target (corresponding to NAL beams of 10^{12} protons per second at 200 GeV) but more extensive redesign may be required to handle the maximum beam intensities and energies proposed. The experiment is now designed to use intensities of about 10^{12} protons per pulse.

All measurements are made as a function of the density of the target. We would use three different densities where the maximum density corresponds to the density of uranium even as the target is composed of 40" of solid uranium. The two other densities are produced by separating the 40 plates of uranium which are 1" thick, by 1" of air and 2" of air respectively. Both intensities and polarizations are then measured as a function of the inverse density of the target. The flux of muons from the decays of pions and K mesons will vary linearly with this inverse density while the flux of directly produced muons will be independent of the density. Then a linear extrapolation of the intensity and polarization to zero inverse density -- or infinite density -- gives the intensity and polarization of the directly produced muons.

As we have emphasized in previous sections, the muons which stop in the detector might originate through at least three physically different sources. There should be a flux of muons produced in the primary interaction through electromagnetic production of muon pairs: these muons will not be polarized along the direction of the beam as the production process conserves parity. There should be an equal number of positive and negative muons produced from this mechanism. Muons may also be produced through the weak interaction decay of very short lived W vector bosons. In the center of mass of the W^+ positive muons will be polarized in the direction of their momentum: they will have positive helicity. Those muons which have very high energies in the laboratory system will retain this helicity.

One also expects a flux of muons from those π or K mesons which decay before they are absorbed through interactions in the target and shield. These muons, which result from the weak interaction decays of pseudoscalar particles, will have helicity opposite to that of muons from W decays. Furthermore, the flux of muons from this source will be proportional to the mean-free-path of the mesons in the target and then inversely proportional to the density of the target. It is well known that the interactions of high energy protons produce many more high energy positive mesons than negative mesons.

The kinematics of the various processes, together with the well known paucity of production of particles with large transverse momenta, require that the muons are produced at angles which are very small with respect to the beam direction. These muons, traveling essentially in the forward direction, will then be deflected by the bending magnet (if such a magnet is provided), pass through enough steel to nearly stop the most energetic muons, and then stop in the detector. The detector has a stopping power corresponding to a spread of incident muon energies of about 1.5 GeV/c. The particles which stop will stop largely in the aluminum of the detector sandwich. The position where they stop will be recorded as the aluminum plate after the last scintillator which is triggered. After a short delay of about 0.1 microseconds, a gate which is about 10 microseconds long is opened and the position of the scintillator which records the decay electron is noted. In this way the longitudinal polarization of the stopped muon is measured. Figure 6 suggests the character of the detector.

The primary measurements will be made in such a manner that only positive muons will be selected. If the magnet is installed, the ratio of positive to negative mesons will be determined primarily by changing the direction of current in the deflection magnet. If it is inconvenient to supply such a magnet, the positive muons are still easily distinguished by their much longer mean life in the aluminum. The mean life of the positive muons in aluminum is about 2.0 microseconds while the mean life of the negative muons will be only about 0.8 microseconds.

The detector will detect about 25% of the decay electrons from the stopping positive muons but only about 5% of the stopping negative muons. Coincidence counters and a hodoscope arrangement will be used to provide some assurance that the muons actually traverse the shield and come from a direction consistent with the possibility that they originated in the target. Backgrounds will be further reduced by appropriate side shielding and shielding of the beam transport tube. We estimate that we require about 15' longitudinally for the detector apparatus and about 10' in width where somewhat more room would be convenient. Shielding against "room" background is quite desirable. We would prefer that the general radiation level at the detector is not greater than a few mr per hour.

We plan to make measurements of muon fluxes at different angles corresponding to different transverse momenta. If a magnet is available different angles will be selected through changes in magnet current leaving the detector stationary. If a magnet cannot be provided we may move the detector small distances. However the effects of multiple scattering are such that the primary measurements of the production angle must be made through the use of direction defining counters placed relatively close to the target. The character of these counters will be considered in detail in the discussion of multiple scattering effects conducted in another section. If signals suggesting W-decays are detected, the variation of the flux of muons with angle will provide information concerning the mass of the W.

Analysis of the Polarization of the Muons

We have noted that the positive muons which result from the decay of the W, and stop in our detector, will be polarized subh that the spin is parallel to the momentum vector of the muon, the positive muons which are derived from the decay of pions or K-mesons will be polarized in the opposite direction. Most of the muons which will stop in the detector will stop in the aluminum plates which will have about 95% of the stopping power. For the purpose of this discussion we will assume that these muons stop uniformly through the thickness of the brass plates and we will neglect the 5% of the muons which stop in the scintillator. Corrections will be necessary for the deficiencies in these approximations but it seems that they can be made rather easily.

We will then proceed to discuss the ideal model where all of the muons are completely polarized and they stop uniformly through the thickness of a aluminum plate which is 4" thick and has a stopping power of about 54 MeV. The muons will decay, with their polarization unchanged, and the electrons will have an angular distribution of $dN/d\theta = 1 + P(x)\cdot\cos\theta$ where θ is the angle between the direction of the momentum of the electron and the direction of polarization of the muon; $P(x)$, the asymmetry parameter, depends on the energy of the electron which we describe in terms of the parameter $x = E/E_m$, where E is the energy of the electron and E_m is the maximum energy kinematically possible. The intensity I also varies with the electron energy. Neglecting corrections for radiative processes the distributions take the form $P(x) = (x - \frac{1}{2})/(x - 3/2)$ and $I(x) \propto 6x^2 - 4x^3$

The average value of the asymmetry parameter, for all of the decays, is 1/3; though the value is one for the most energetic electrons the parameter changes sign for the least energetic electrons. Since the most energetic electrons have a much larger chance of escaping the brass plate and registering in the scintillator there is actually a bias towards higher asymmetries. We have measured that about 25% of the electrons will emerge from the plate and that the average asymmetry of this sample will be equal to -0.40. The fore-aft asymmetry will then be equal to

$$(1 + P/2)/(1 - P/2) = 1.5$$

Multiple Scattering

As a result of multiple scattering the muons which pass through the shielding are deflected appreciably and the magnitude of this deflection in space and in angle must be estimated in order to consider effects pertinent to the experimental design. Though a more careful calculation is desirable, and should eventually be made, probably by Monte Carlo methods, these estimates are probably reasonably reliable and suggest that multiple scattering effects are quite important in considering the angular resolution of the apparatus and then the resolution in transverse momentum.

A basic relation for the angular deviation in a specific direction of a unit charged particle moving at relativistic energies through a length x of material with a scattering length of x_o can be written as

$$(\bar{\theta})^2 = \tfrac{1}{2}\,(21\cdot 10^{-3}/P)^2\cdot(x/x_o)$$

where P is the momentum of the particle in GeV/c. It is convenient to use a unit of length which represents an ionization loss of 1 GeV. For iron, this will be equal to about 500 gms/cm^2 or 35 radiation lengths or 64 cm.

Then we can write $P = P_o(L - x)/L$ where P_o is the incident momentum of the muon, taken here as 2 GeV/c greater than the thickness of the shield L. The total angular deviation of 170 GeV muons, upon passing through the shield, will then be equal to

$$(\bar{\theta})^2 = \tfrac{1}{2}\,(21\cdot 10^{-3}/P_o)^2\cdot 35\cdot(172)^2 \int_0^{L-2} dx/(L - x)^2$$

the integral is equal to $\int_{182}^{2} dx/x^2 \approx \tfrac{1}{2}$ and $(\bar{\theta})^2 \approx 36\cdot 10^{-4}$

and $\bar{\theta} \approx 0.06 \approx 10^{o}$.

This scattering is dominated by the last few meters of steel and is not, then, to be compared with the deviations which affect greatly the transverse momentum resolution. Nevertheless, the results show that there will be some advantage if some appreciable thickness of a lighter substance than iron is placed before the detector.

An angular deflection of θ radians at a distance s from the end of the shielding can be translated into a spatial deflection of $\theta\cdot s$ of the particle at the end of the shielding. If we write the mean square displacement in a y-direction as $(\bar{y})^2$ we have

$$(\bar{y})^2 = (\theta\cdot(L-x))^2 = \tfrac{1}{2}(21\cdot10^{-3}/P_o)^2\cdot L^2\cdot 35\cdot dx$$

is the mean square displacement induced if the particle traverse one unit dx of iron. The total displacement of 170 GeV muons will then be about equal to

$(\bar{y})^2 = \tfrac{1}{2}(21\cdot10^{-3}/P_o)^2\cdot 35\cdot L^3 = 1.0$ and $\bar{y} = 1.0$ GeV units or

$\bar{y} = 0.65$ meters for 350 GeV/c muons, $\bar{y} \approx 1.0$ meters.

In general, the root mean square deviation in position for a particle which loses all of its energy in an absorber varies as the square root of the length of the absorber or, equally, as the square root of initial energy of the particle. Translated into transverse momentum, the scattering displacement for a 10 GeV/c particle passing through iron is about equal to 1.0 GeV/c: for a 350 GeV/c muon, the spread will be about 1.5 GeV/c. These numbers mean that one cannot obtain resolution in transverse momentum by the angle of acceptance of the detector if the detector is to accept stopped particles. However, it is possible to use counters closer to the source to define the momentum of the particles which stop at the end of a long absorber. Here the scattering varies inversely with the momentum in the same way as the magnetic deflection. We propose to define our acceptance transverse momentum with such counters.

We have noted that the intensity of muons derived from meson decays falls off very fast with respect to transverse momentum. Indeed, it is a good approximation to consider that the intensity varies exponentially with transverse momentum with a mean momentum of about 0.5 GeV/c. Since the variation of intensity with angle of muons from massive W's, does not vary with momentum so sharply, it is desirable to be able to make measurements at large momentum transfer -- perhaps at transfers of the order of 2.5 GeV/c. However, if the multiple scattering is large, it is clear that it will not be possible to make full use of the advantages of working at an angle. It is then essential, to define the production angle in a more certain way than by simply noting the position of the particle emerging from the shield and then the angle as measured at the detector.

It seems that it is very useful, and not too difficult, to measure the angle of production comparitively near the point of production where multiple scattering effects are not so important. We consider, explicitly, the design of counters to be placed 40 meters down stream from the target. The mean displacement $\bar{y}$ due to multiple scattering upon passing through a length x of material can be expressed as

$$(\bar{y}^2) = \theta_s^2 x^3/96 \qquad \text{where} \qquad \theta_s^2 = (21\cdot10^{-3}/P)^2(1/x_o)$$

and x_o is the radiation length. Taking the radiation length in iron as 15 gms/cm^2 or about 0.02 meters, $\theta_s^2 = 10^{-6}$ for an initial momentum of about 180 GeV/c and for x = 40, $\bar{y}$ = 2.6 cm. For muons with an incident energy of about 350 GeV, $\bar{y}$ = 0.9 cm. In terms of transverse momenta, at 170 GeV/c, the mean scattering is equivalent to about 100 MeV/c and at 400 GeV/c, the scattering angle is about the same, 100 GeV/c. The root-mean-square scattering angle varies as 1/P as does the angle corresponding to a given transverse momentum.

We would then plan on placing a set of counters in a slot in the shield about 40 meters down stream from the target and these counters would define the transverse momentum of the muons. For operation at 200 GeV, we would plan on placing 10 counters about 3" wide and about 12" deep in the slot. For operation with 500 GeV incident protons we would use 10 counters 1" by 12". The use of the counters would depend upon the counting rate in the detector. Probably the counters would be registered and all particles passing through the counters would be counted in the detector but the further information, fed into the computer, would be used to determine the transverse momentum of the muon registered in the detector.

Another set of counters would also be desirable further down stream so that the intensity of muons which pass through to the final detection stage can be defined by three sets of counters and then triple coincidences.

Muon Flux and Counting Rates

The polarization detector subtends an effective area of about four square feet or 0.36 m^2. When set to detect 350 GeV/c muons, the detector will be about 700 ft. from the source and the effective solid angle will be about $8 \cdot 10^{-6}$ steradians. The effective stopping power of the detector will be about 1.4 GeV. Let us assume that the incident proton flux will be 10^{12} per pulse and that the total nucleon-nucleon interaction cross section (neglecting diffraction scattering) is about $3 \cdot 10^{-26}$ cm. Then one count per pulse in the detector will correspond to a production cross section

$$d\sigma/d\Omega dE = 2.5 \cdot 10^{-33} cm^2/ster \cdot GeV$$

We believe that we can measure the polarization of the muons with an error of 0.30, if there is no substantial background, from a sample of 4000 counts in the detector. Since we are primarily attempting to distinguish between polarizations of 1.0, 0. and -1.0, this would be sufficient to establish an effect. At a rate of 1000 pulses per hour, we could then measure the polarization of any process which contributed an effective muon cross section of $5 \cdot 10^{-35} cm^2$ in 200 hours of measurement.

The measurement of the "intercept" using the large area counters would be more sensitive by a factor of about 1000; a factor of four from the larger area, a factor of about 25 for the larger momentum bite and a factor which depends upon the background, but which we take conservatively as 10, because of the greater statistical significance of the flux measurements as compared to the polarization measurements. We should then be able to detect an anomalous contribution to the muon flux of a magnitude corresponding to a production cross section of about $5 \cdot 10^{-38} cm^2/ster \cdot GeV/c$.

The background should result primarily from the decay of mesons. The effective production cross section can be estimated as about equal to $10^{-32}\exp(-2.5\cdot p_t)$ cm^2/ster·GeV/c, where p_t is the transverse momentum in GeV/c. For a value of p_t of about 2.5 GeV/c, the cross section will then be about equal to $2\cdot 10^{-35} cm^2$/ster·GeV/c. In the presence of this back ground, the sensitivity of the polarization measurements would not be strongly affected but the results of the intensity measurements would be limited to a sensitivity which would correspond to about $10^{-37} cm^2$/ster·GeV/c.

We propose that we would operate for about 100 hours of beam time. At the end of this time we should have very accurate measurements of the flux of muons which originate very near the point of interaction of the protons in the target. Operationally, we shall then have measured the "intercept" flux, which is the flux of muons extrapolated to infinite target thickness. If this flux is zero, within experimental error, we can conclude to the accuracy of these measurements that there is no anomalous production mechanism which produces muons directly with a cross section larger than that set by the accuracy of our measurements; i.e., about 10^{-37} cm^2/ster·GeV/c. If there is evidence for a substantial production of prompt muons, then the experiment can be extended so as to provide a measure of the polarization of this sample and an identification then of the origin of that flux. We can presume that another 200 hours of time might be expended in such a search though that might be extended substantially if there is strong evidence for a very striking anomaly.

Our techniques are such that our results are obtained essentially on-line. We need no long analysis to determine the course of our measurements.

E_p	M_W	$d\sigma_\mu / dE_\mu d\Omega$ maximum (B.E)	σ_t (B.E.0	σ_t (Diff)
200	6	$2.5 \cdot 10^{-35}$	$1.8 \cdot 10^{-36}$	10^{-34}
200	9	$9. \cdot 10^{-37}$	$5. \cdot 10^{-38}$	$7.5 \cdot 10^{-35}$
200	12	$3. \cdot 10^{-40}$	$2. \cdot 10^{-41}$	$5. \cdot 10^{-35}$
500	6	$1.1 \cdot 10^{-35}$	$1.7 \cdot 10^{-36}$	10^{-34}
500	9	$6. \cdot 10^{-36}$	$1.0 \cdot 10^{-36}$	$7.5 \cdot 10^{-35}$
500	12	$1.1 \cdot 10^{-36}$	$1.7 \cdot 10^{-37}$	$5. \; 10^{-35}$
500	15	$5. \cdot 10^{-42}$	$1.4 \cdot 10^{-41}$	$3.5 \cdot 10^{-35}$

Table I Some differential cross sections and total cross sections for the production of muons from the decay of the W where the W production cross section is calculated from the baryon exchange recipe for the diagram of Fig. 2c (B.E.) and the diffraction disassociation recipe for the diagram of Fig. 2d (Diff). These cross sections are calculated on the (unrealistic) assumption that the branching ratio for the W decay to a muon is one and the results must then be modified by multiplication by a factor B, the brancing ratio.

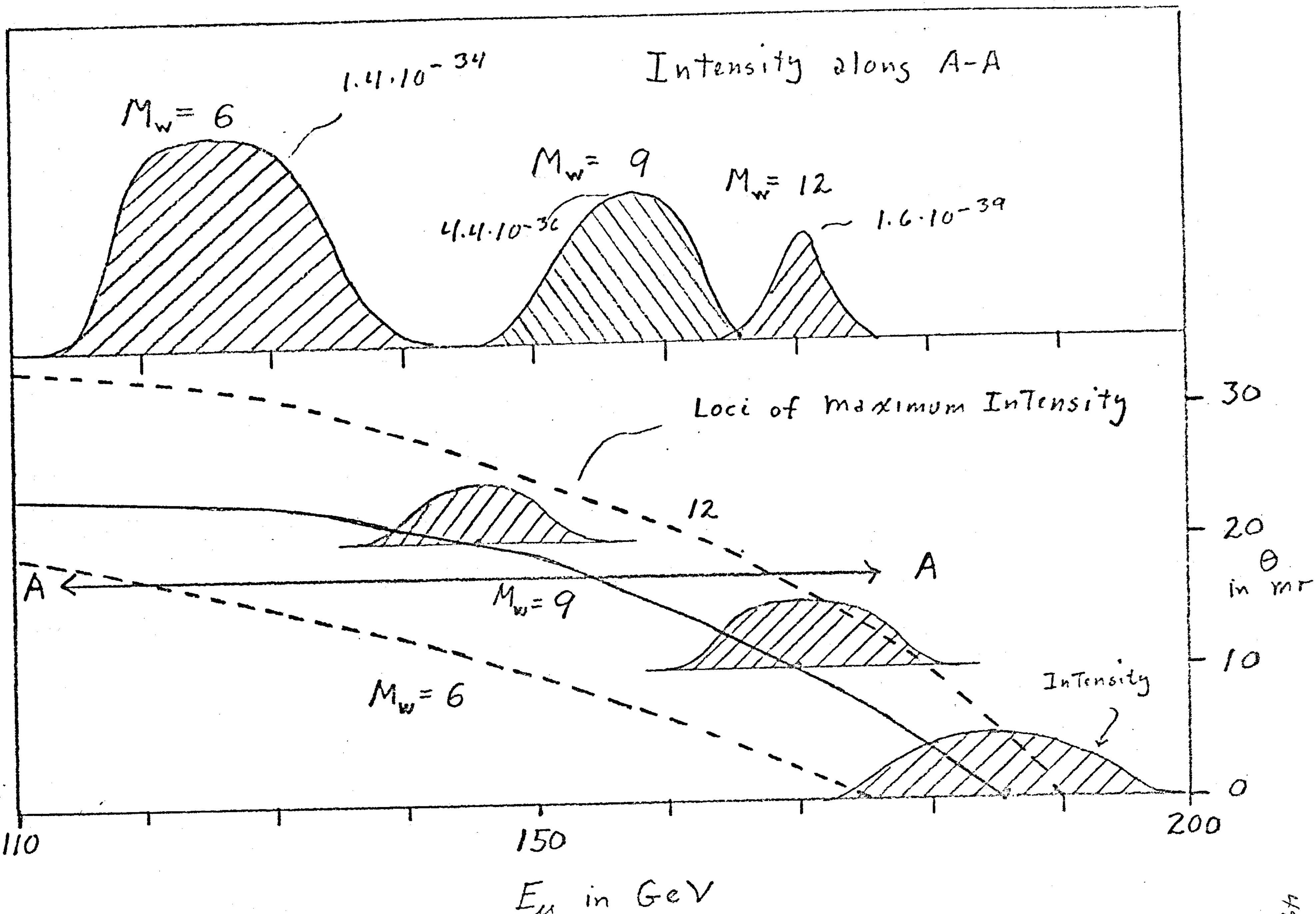

Fig.3 Characteristic curves of muon intensities from W-decays as a function of muon energy, angle, and W-mass. The incident energy is 200 GeV.

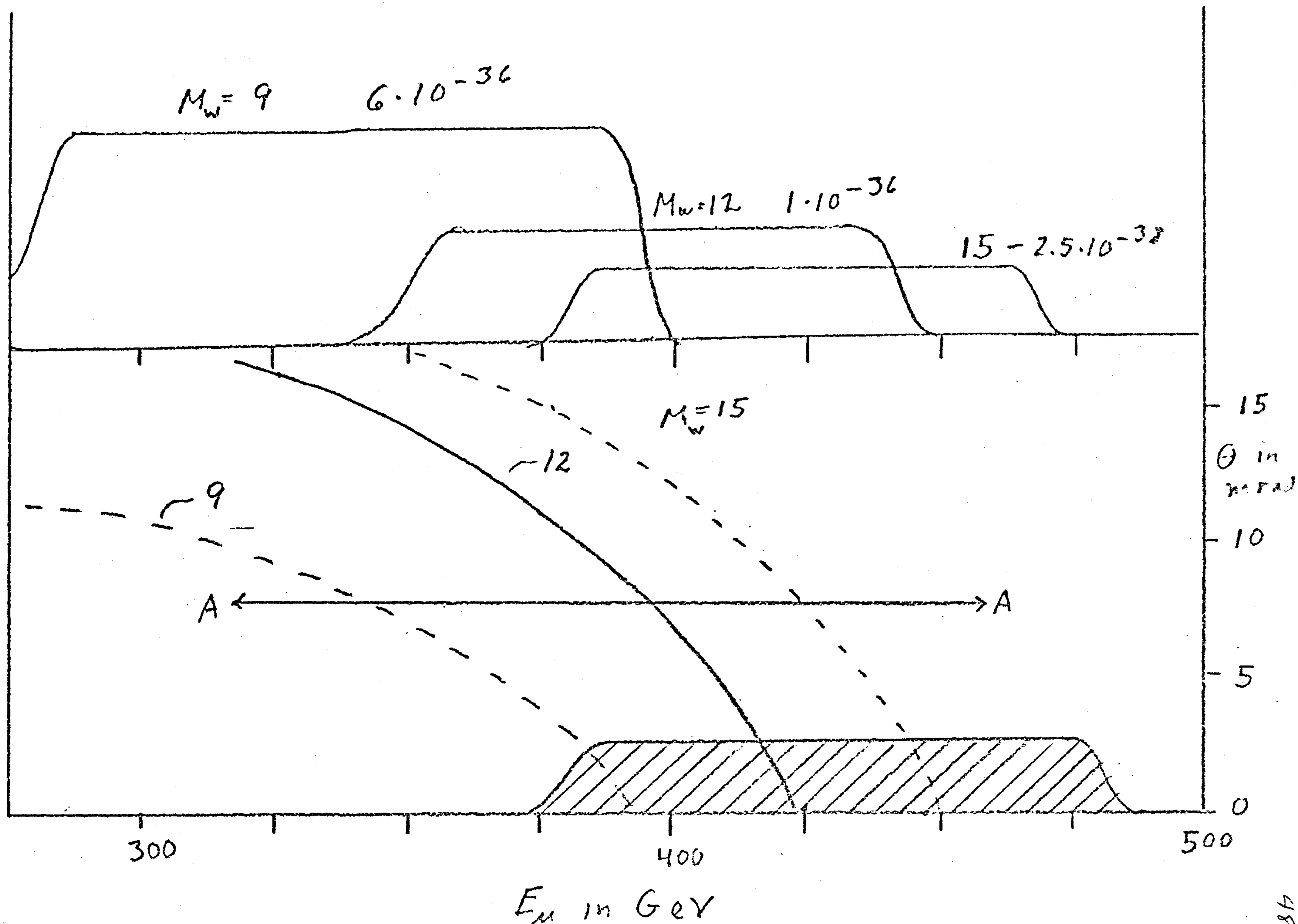

Fig. 4 Characteristic curves of muon intensities from W-decays as a function of angle, muon energy and W-mass. The incident proton energy is 500 GeV.

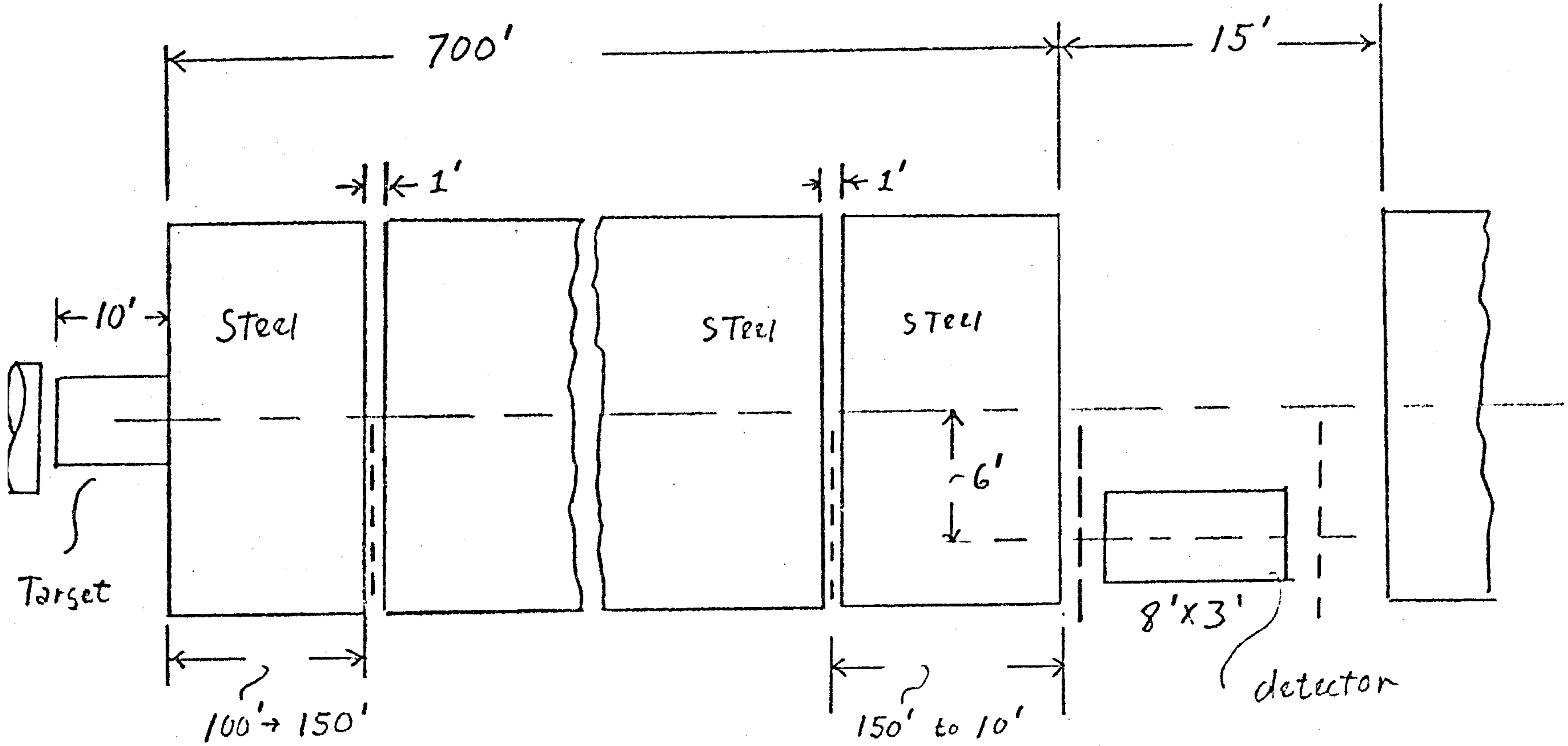

Fig. 5. Schematic Drawing of experimental set up in area I

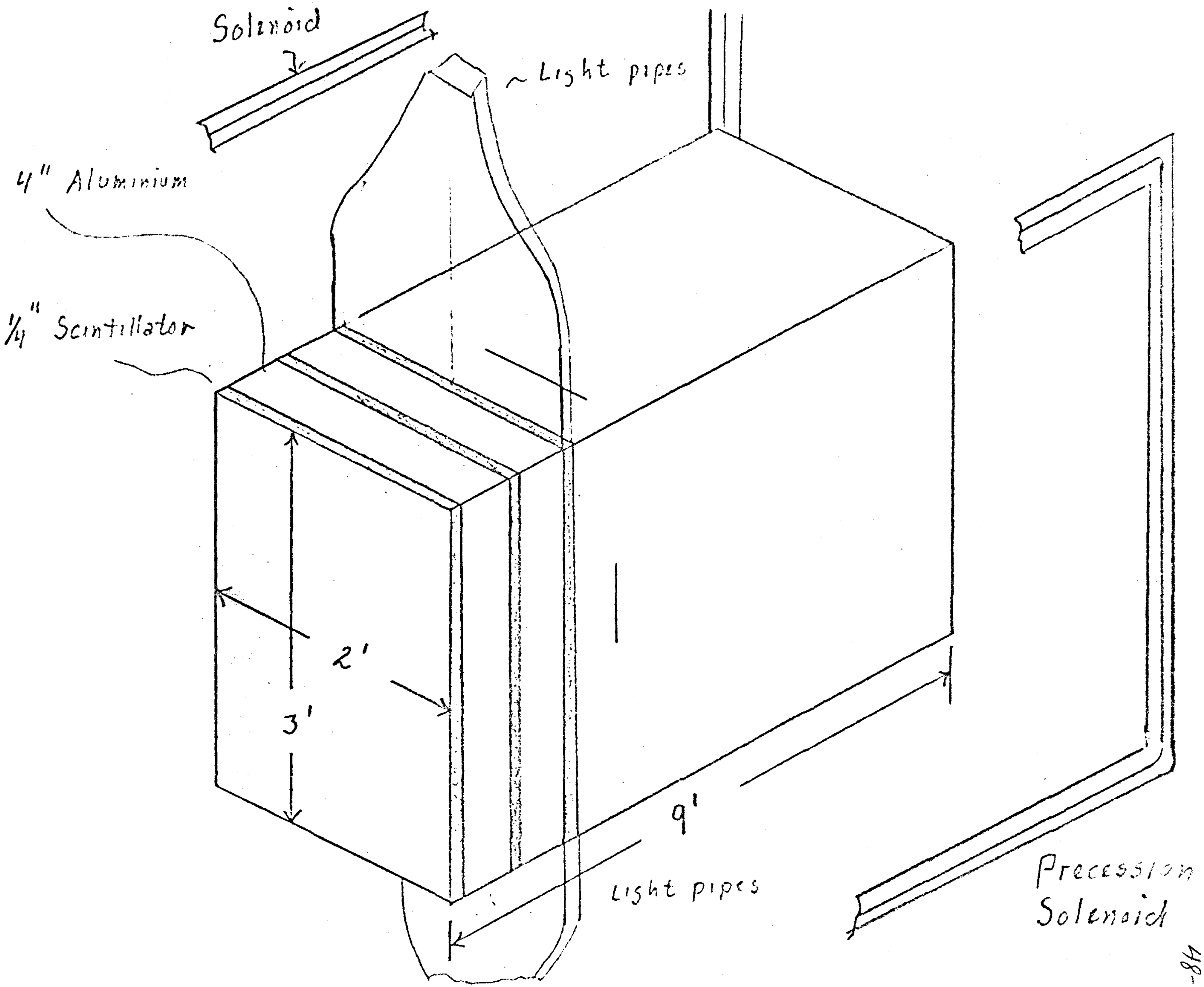

Fig. 6. Polarization Detector

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Addendum to Ex. 48

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Abstract

Experiment 48 is reexamined in view of the discovery of the two neutral meson states at 3.1 GeV and 3.7 GeV which decay into lepton pairs. The apparatus of Ex. 48 can be considered as a two-armed spectrometer with extremely large aperture but with modest energy resolution, rather inflexible energy variation and with modest invariant mass resolution: dM/M is typically 25%. It is shown that the the muon pairs from the decay of the 3.10 GeV state will be detected in coincidence at a rate of about 5 counts per pulse of 10^{12} protons if the cross section is no larger at FNAL energies than at 30 GeV; $B\sigma = 10^{-34}cm^2$. If the cross section for the production of muon pairs from the 3.7 GeV state is not much less than 20% of the flux from the 3.10 GeV state, the 3.7 GeV state will be easily detected. The polarization of the muons from the decays of these states can be measured if the cross sections are not smaller than the values listed here. Muon decays from possible heavier states can be detected and the masses of these states can be determined if the flux of muons is not much less than 5% of the flux from the 3.1 GeV state. The polarization of muons from the decays of possible new charged states can be measured if the production cross section is again of the order of $10^{-34}cm^2$ and the anomalous polarization of these muons can be used as evidence that such states exist.

Experiment 48 -- Addendum

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I Introduction

The recent discovery of the narrow mesonic states near 3.1 GeV and 3.7 GeV are naturally relevant to Ex. 48 which was designed to detect new states. While the basic program of measurement for Ex. 48 probably should not be changed in any fundamental manner, an awareness of the existence of these new states changes certain expectation probabilities and then certain experimental emphases. In particular, there is now, and may still be in the near future, an interest in the polarization of the muons produced in the decays of the new states. Furthermore, the existence of these neutral states strongly suggests the existence of new charged states which are not so easily detected by the SLAC and Brookhaven experiments. We must also presume that there is some possibility that more massive neutral and charged states may exist accessible at FNAL energies but not within reach of the previous experiments.

The design of Ex. 48 is such that the apparatus can be considered as a muon spectrometer with enormous angular aperture and solid angle but with modest energy resolution and modest invariant mass resoultion. Moreover, the polarization of the muons can be measured at one arm. While the sensitivity of the apparatus towards the detection of new particles is necessarily model dependent -- that is dependent upon the particular production and decay systematics of the particles -- we can write down approximate detectable cross sections for orientation where the numbers appended are discussed in detail in following sections. We discuss the sensitivity in terms of $B\sigma$, the total production cross section for the particles σ times the branching ratio for the decays into muons B. Then states which decay into muon pairs can be detected at levels $B\sigma \approx 10^{-36} cm^2$. Massive states which decay into single muons can be detected at about the same level, $B\sigma = 10^{-36} cm^2$, though with less certainty as to the character of the state. The polarization of muons, either from pairs or singly produced, can be measured at productio levels $B\sigma$ of about 10^{-34} cm^2. These are conservative numbers, for certain plausible models of production of these particles and other particles which contribute to backgrounds, lower limits could be established.

II A Production Model for New Particles

Although we have no particular insight in the mechanisms for the production of any particle in hadron-hadron interactions, we do have the results of observations of production systematics and it seems sensible to presume that the inclusive production of new particles follows much the same pattern as for the inclusive production of pions, K-mesons, anti-protons, etc. For our purpose, we can consider that all of these particles are produced with a cross section in the center-of-mass system of the form

$$d\sigma/dx = \tfrac{1}{2}\sigma A \exp(-Ax) \qquad (2$$

where x is the Feynman variable, p_L/p_{Max}, and A is taken as 8, the same as for positive pions and positive K-mesons. The results are not very sensitive to the value of A for $10 < A < 5$.

We believe that in our experiment, the transverse momentum distribution of the produced particles is likely to be masked by the pseudo-transverse momentum derived from the multiple scattering of the muons in the target and the associated materials near the target. Although the effective multiple scattering differs to some extent depending upon the precise placment of counters near the target, we used a canonical transverse momentum distribution for each muon of the form:

$$dN/dp_t = C \exp(-p_t 2/p_o{}^2) \qquad (2$$

where p_t is the transverse momentum of the muon induced by multiple scattering and the production distribution of the parent state (but not by the decay from the parent state), p_o was taken as 0.5 GeV/c and C was the appropriate normalization constant. The effective spread in production angle of a parent particle would then be about 0.707 GeV/c from both multiple scattering and intrinsic production transverse momentum.

The calculations which were conducted to provide insight into the relation between the measurements contemplated in Ex. 48 and phenomena induced by existence of new particles were made in a standard manner, using Monte Carlo techniques, from the production recipes listed above. In particular, a state of a given invariant mass was selected from a distribution of the form of Eq. 1, the decay of the state into two light particles of which one or both are muons was then calculated assuming that the decay distribution was isotropic in the center-of-mass system of the parent particle. The momentum of the product (muon) states in the laboratory was then calculated and a transverse momentum selected from a distribution defined by Eq.2 was added (or subtracted) from the transverse momentum initiated by the decay process. The muon was then followed through the apparatus and the probability of the muon intersecting the counters was calculated in a conventional manner so as to develop the distribution presented in Figs. 1, 2 and 3.

III Results of the Calculations

The results expressed in the graphs of Figs. 1, 2, and 3 represent counting rates per pulse assuming a flux of 10^{12} protons per pulse and a cross section per nucleon as stated on the figures. These numbers are then supposed to be representative numbers and it is not intended that they be used as definitive values of counting rates. We expect that they are accurate to about a factor of 5, however, barring highly anomalous production mechansims (which could make the counting rates higher or lower).

The graph of Fig. 1 shows a coincidence rate for muons with energies sufficient to reach the back detector (E > 150 GeV) and the middle dtector array (E > 50 GeV). The rate corresponds to coincidence rates for a muon passing through the 6' by 6' counter at 1200' and one 2' x3' counter at 400'. The rate, for each specific invariant mass is presented as a function of opening angle (which will then be almost invariant with respect to the angle of production of the primary parent particle). Since the back counters are nominally fixed at an angle of 23 mr, the actual scanning will be accomplished by a combination of multiple scattering in the dirt between the angle determining counters at 400' and, more important, by magnetic deflection using the bending magnet near the target as planned previously. The precise deflection of the slower muon will depend upon the precise placement of that magnet which is not completely defined as of Dec. 20, but this muon will pass through less field and will not be deflected beyond the angles supbtended by the 400' array. In general, the rates of the order of 50 counts per pulse for a one nanobarn branching ratio-cross section are indicative of the sensativity of this kind of detection. With such a counting rate, the ultimate sensativity would be expected to be of the order of 10^{-36} cm^2.

The backgrounds from pairs of muons derived from pairs of pions which decay to muons should be small. The probability of a pion decaying to a muon of energy E before interacting with the material in th target is about equal to $3 \cdot 10^{-3}/E$, where E is measured in GeV. The probability of a pion pair with an invariant mass M simulating a muon pair with such an invariant mass would then be about 10^{-9}. Then, even for a production cross section of pion pairs with a large invariant mass as great as 10^{-27} cm^2, the backgrounds would correspond only to muon pair cross sections of the order of 10^{-36} cm^2. By measuring the rate as a function of charge density, even such a background would be easily detected and subtracted -- the background of muon pairs from pion decay would vary as the inverse of the square of the density.

Actually, the sensitivities available are probably far in excess of what can be used to detect high mass neutral states which might decay into two muons as the tails of the 3.07 GeV state production would interfere on a higher level. Even if the cross section for production of the 3.07 GeV state times the branching ratio were no larger at 300 GeV than at 30 GeV -- that is 10^{-34}cm^2 -- the counting rate from that state would be quite high, perhaps of the order of several counts per pulse, and the tail of that counting rate extending to large opening angles as a result of multiple scattering of the muons in the target system would probably hold the sensitivity to more massive states to levels not much lower than 10^{-35}cm^2, and much larger cross sections for the production of the 3.07 GeV state would further reduce the sensitivity for finding more massive states.

The recording of coincidences between memebers of the counter arrays at 400' (with a threshhold of about 50 GeV) are also useful in detecting massive states which decay into two muons. The diagram of Fig. 2 shows the counting rates as a function of opening angle where the rates represent the rates for interaction with two 2' by 3' counters. Each counter then subtends about 5 mr so the integral under the curves for each invariant mass are a measure of the total counting rates for a cross section of 10^{-33} cm^2. Typically, this rate may be of the order of 100 counts per pulse at an invariant mass of 3 GeV and half of that at 7 GeV. Even more than for the 150-50 GeV measurements, the tail of the rates from the well known 3.07 GeV state will obscure production from higher mass states. We could probably expect to detect a higher mass state if the value of $B\sigma$ were 1/10 of that for the 3.07 GeV state.

Larger fluxes are required for the polarization measurements inasmuch as both the solid angle and the momentum bite is smaller. The graph of Fig. 3 show the rate of stopped muons in the polarimeter as a function of opening angle for various invariant masses. Here, the canonical cross section is taken as 10^{-31} cm^2 and the maximum rates of about 10 counts per second for a 3 GeV invariant mass are relevant to polarization measurements of the muons from 3.07 GeV state. Roughly speaking, the error in the polarization will be of the order of $E_p = 5/\sqrt{n}$ where n is the number of muons stopping in the polarimater. Since only positive muons are useful, another factor of 2 enters if all muons are considered and 10,000 stopping muons will give a polarization measurement accurate to about 5%. We can then expect to get an adequate measure of the polarization of muons from the 3.07 GeV state for a cross section $B\sigma = 10^{-34}$cm^2 in 100 hours of running and if the cross section is appreciably larger than this value measured at 30 GeV, the polarization can be measured quite easily. Again, the background should be completely negligible at an equivalent level of 10^{-36} cm^2.

Of course, much of the interest is now focused on the possible existence of charged particles of large mass and very narrow widths which will presumably decay through the weak interactions. Muon decay will presumably be an important decay channel and these muons will be polarized almost completely in the "natural" polarization; (i.e. positive muons will have a positive helicity) for the decays into three or more particles. Charged vector particles may decay into a muon and a neutrino in which case the muon would again have a natural helicity but the decay of scaler particles into a muon and neutrino would result in the opposite polarization even as for pions and K-mesons. If the parent particle were quite heavy, this decay would be weak however. The graph of Fig. 4 shows the intensity of muons which stop in the polarimeter as a function of angle for two-body dcays of states of different invariant mass. Actually, we expect that three-body decays may be more important but the muon decay energy in the center-of-mass system of the parent particle will peak sharply towards the highest kinematically available energies so these curves are not grossly inadequate for the three body decays. Note that the canonical cross section for this graph is $10^{-33}cm^2$ which suggests that such states can be detected by the anomalous polarization of the prompt muons which they emit upon decay.

Here the background problem is more complex. The discrimination against muons from pion decay is of the order of $2 \cdot 10^{-5}$ and if there were no further discrimination, the detectable cross section would not be much less than 10^{-5} of the pion cross section or perhaps $5 \cdot 10^{-31}$ cm^2. If the mean transverse momentum is large, the discrimination against pions would be much greater and levels of the order of 10^{-32} seem accessible. However, we already have some evidence for the existence of a flux of prompt muons with an intensity of the order of 10^{-4} times the pion intensity. The polarization of that flux would be easily measureable out to transverse momenta near 3 GeV/c. If this flux is not derived from the decays of new particles but is a consequence of a larger flux of heavy, virtual photons than we have expected, muons from this source could mask small contributions from new particles.

IV Summary

We can expect to detect muons from the 3.07 GeV state by our coincidence methods and the flux should be quite large. This flux will obscure a contribution from the 3.7 GeV state if that intensity is not greater than 25% of the intensity from the 3.07 GeV state decays. If there are larger mass states which decay into two muons with a production cross section times branching ratio as large as 10% of the 3.07 GeV state, these states would probably be resolved.

The polarization of the muons from the 3.07 GeV state should be easily measured. In any simple description of this state, such a measurement would not provide different information that derived from the measurements of the fore-aft asymmetry at SLACK. While we believe that these measurements are almost certainly valid, we note that the Frascatti group has contradictory results.

If heavier states decay to two muons with values of B not smaller than 10% of the value for the 3.07 GeV state, we can measure the polarization of themuons from these states.

We can expect to measure the polarization of the prompt muons from the decays of any new charged states down to cross sections of the order of 10^{-34} cm^2 where the fundamental limit is likely to be backgrounds from other sources of prompt muons.

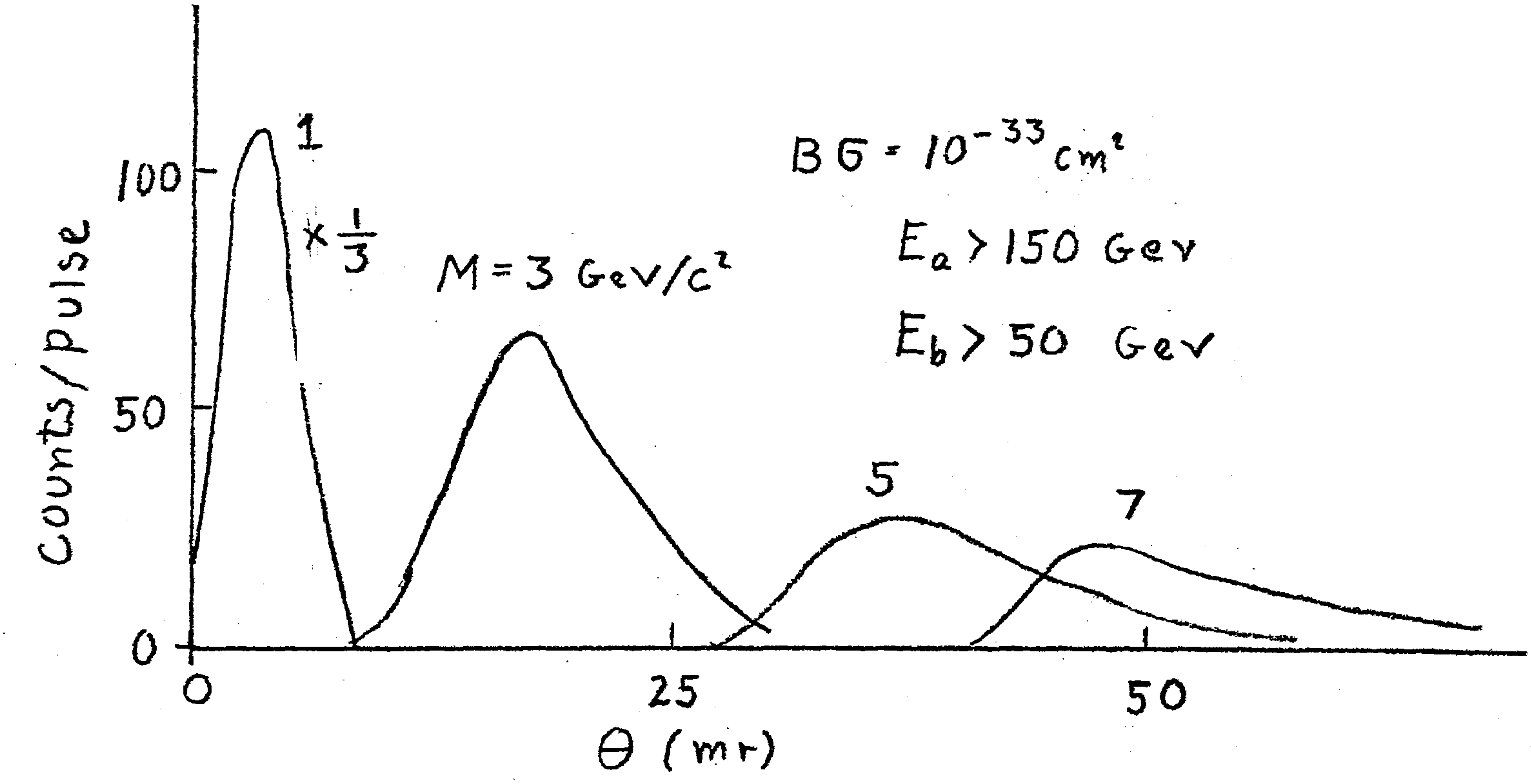

Fig. 1 Counts per pulse plotted against opening angle where one muon has an energy greater than 150 GeV and one greater than 50 GeV corresponding to the back counters and middle counters.

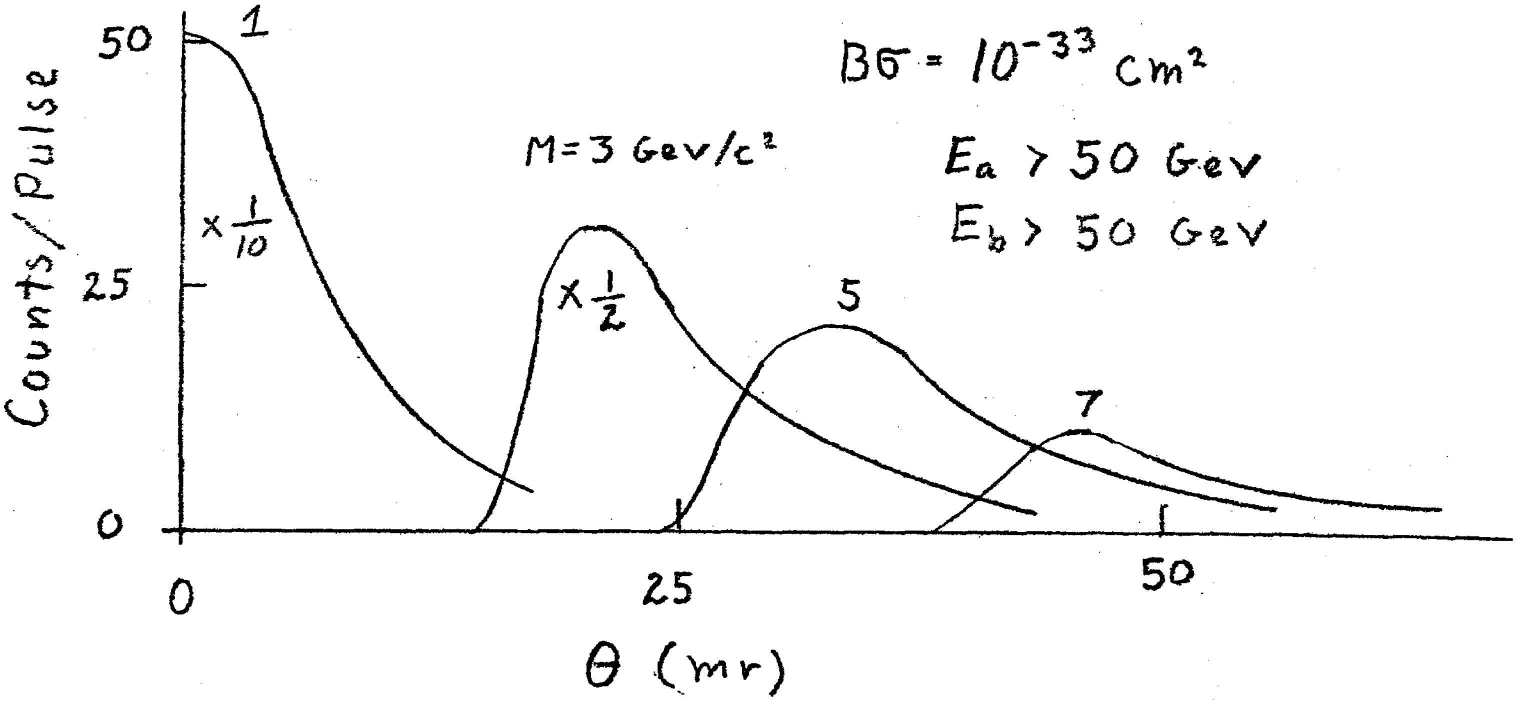

Fig. 2 Counts per pulse plotted against opening angle where each muon has an energy greater than 50 GeV and then passes through one counter in the middle counter array.

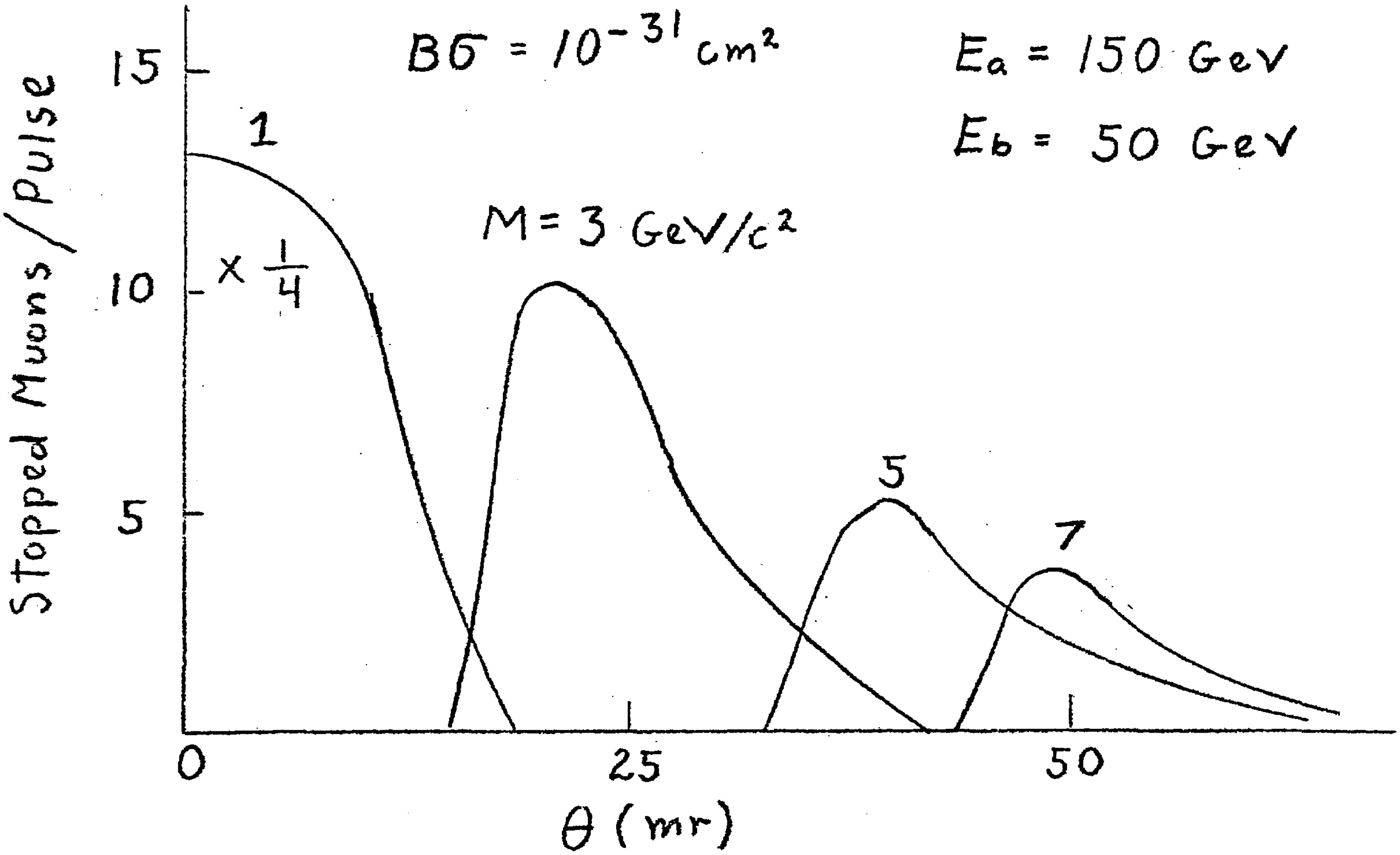

Fig. 3 Number of muons per pulse which stop in polarimeter in coincidence with a muon passing through a counter at the 400' level.plotted against the opening angle. Note the canonical cross section is taken here as $B\sigma = 10^{-31} cm^2$.

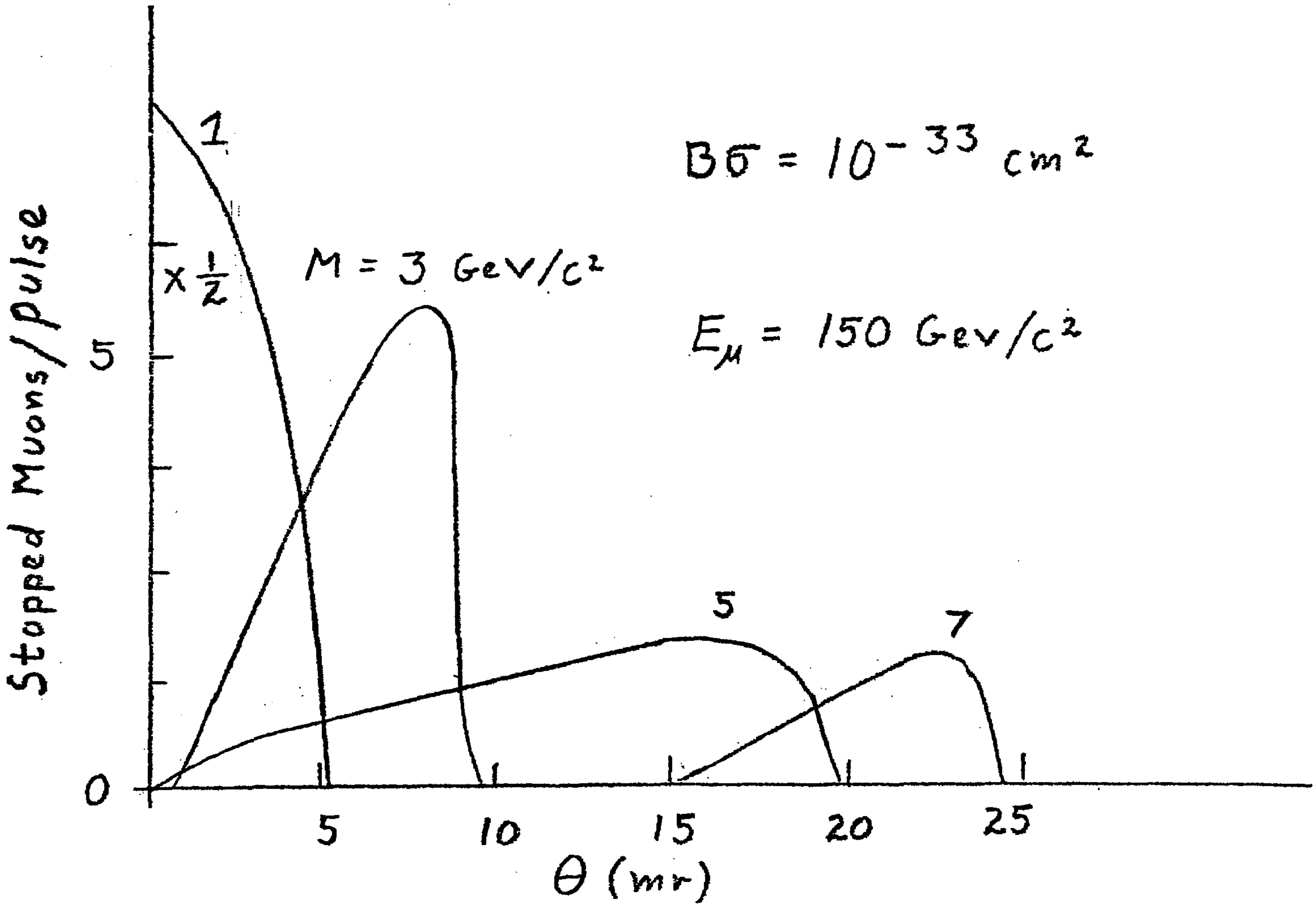

Fig. 4 Number of stopped muons per pulse in the polarimeter for two-bc[illegible] decays of states of invariant mass M.

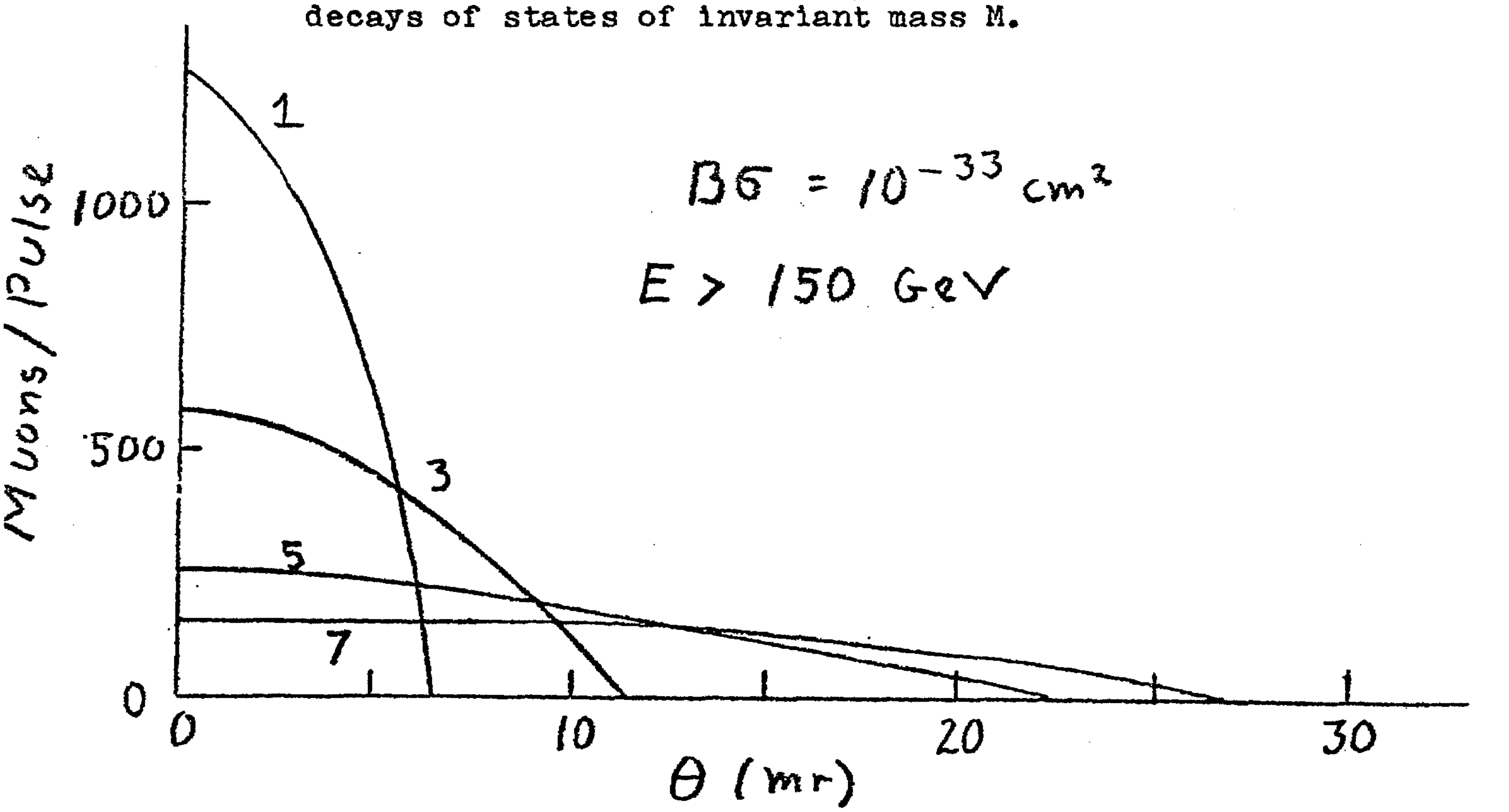

Fig. 5 Counts per pulse in 6'X6' back counter from muons derived from the two-body decays of particles with invariant mass M